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Combining empirical and theory-based land-use modelling approaches to assess economic potential of biofuel production avoiding iLUC: Argentina as a case study

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ABSTRACT

In this paper, a land-use modelling framework is presented combining empirical and theory-based modelling approaches to determine economic potential of biofuel production avoiding indirect land-use changes (iLUC) resulting from land competition with other functions. The empirical approach explores future developments in food and feed production to determine land availability and technical potential of biofuel production. The theory-based approach assesses the economic performance of biofuel crops on the surplus land in comparison with other production systems and determines the economic potential of biofuel production. The framework is demonstrated for a case study in Argentina to determine the development of biofuel potential from soy and switchgrass up to 2030. Two scenarios were considered regarding future developments of productivity in agriculture and livestock production. It was found that under a scenario reflecting a continuation of current trends, no surplus land is expected to become available. Nevertheless, the potential for soybean biodiesel is expected to keep increasing up to 103 PJ in 2030, due to the existence of a developed agro-industrial sector jointly producing feed and biodiesel. In case large technological developments occur, 32 Mha could become available in 2030, which would allow for a technical potential of 472 PJ soybean biodiesel and 1445 PJ switchgrass bioethanol. According to the economic assessment, an economic potential of 368 PJ of soy biodiesel and 1.1 EJ switchgrass bioethanol could be attained, at a feedstock production cost of 100–155 US$/ton and 20–45 US$/ton, respectively. The region of southwest Buenos Aires and La Pampa provinces appeared to be particularly promising for switchgrass. The ability of jointly assessing future developments in land availability, technical and economic potential of biofuel production avoiding iLUC and spatial distribution of viable locations for growing biofuel crops means that the proposed framework is a step forward in assessing the potential for biofuel production that is both economically viable and sustainably produced.

Contents

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1. Introduction

Governmental measures have been introduced in several countries to promote the production and use of biofuels, mainly in the form of tax reductions/exemptions and mandatory blending targets [1]. As a result, a further expansion of biofuel deployment and trade into transportation energy systems is expected in forthcoming years [2]. However, there is an ongoing debate in scientific and political arenas on whether negative aspects of biofuel production might outweigh their benefits. Particularly, competition for land between dedicated bioenergy crops and food production has been observed [3] and is anticipated to increase in forthcoming years [4]. Competition for land between food and biofuel production seems to arise from the combination of growing and changing demand for food, increasing global energy demand for transportation and the need to reduce greenhouse gas emissions [5]. Land competition can result in several undesired impacts: food security issues due to volatility of food prices [6], particularly in developing countries [7]; decline in biodiversity [8]; carbon losses due to both direct land use change [3,9] and indirect land use change (iLUC), i.e. land clearing resulting from displacement of food production to new areas [4,10]. Therefore, the search for beneficial biofuels should focus on feedstock options that avoid these impacts [2,11].

Several methods have been developed to assess the potential for biofuel production and its environmental performance at various scales. Non-spatial assessments of future global and regional bioenergy potential have been conducted [12–14], but this type of approach is not able to incorporate features that characterise land-use systems such as local landscape heterogeneity and complex interactions between land-use driving forces [15,16], and therefore neglects the importance of location in the production potential, economic viability, and environmental performance of bioenergy production [17,18].

Spatially-explicit land-use modelling approaches have been developed to study the potential and impacts of biofuel production, with considerable differences in terms of theoretical background, temporal and spatial scale and range of applications. A coarse distinction between theory-based and empirical models can be made while reviewing modelling approaches [19–21]. Theory-based approaches apply a structured theory to a real case study to guide the characterisation of land-use change processes and explain the casual relationships between decisions on land-use and their outcomes. On the other hand, empirical models construct hypothesis about the relation between land-use patterns and its explanatory factors through fitting of empirical spatially-explicit data and extrapolate historical land use trends into the future.

Theory-based approaches typically assume that decisions on land-use aim to maximise expected returns or utility derived from land, often using the economic theory to choose the model's functional form and explanatory variables [19]. Optimisation models applying techno-economic algorithms have been used for allocation of bioenergy crops and biofuel plant siting (e.g. [22,23]), but these models put the emphasis on the economic drivers, while dealing with spatially-explicit biophysical drivers for crop production at fairly coarse resolutions. Therefore, they somewhat neglect the importance of spatial variation of biophysical parameters on the biofuel production potential. van der Hilst et al. [17] proposed a method to perform detailed spatially-explicit assessments of the economic performance of biofuel crops in comparison to other existing food production systems. However, this method is rather static and does not take into account the dynamic developments of land use systems in time and thus is not able to determine the potential that could be attained without endangering future food security.

A large number of empirical land use models have been applied in recent studies to dynamically simulate future spatial distribution of agricultural production and determine direct and indirect land-use changes resulting from pre-determined volumes and/or policy targets of biofuel production (e.g. [10,24–27]). While focusing on assessing the environmental impacts of biofuel production targets, these approaches are not suited to determine the biofuel potential that could be produced without causing iLUC. The PCRaster Land Use Change (PLUC) model has been developed to perform spatiotemporal assessments on the development in land availability for bioenergy crops, according to expected demand for food commodities, dynamics of several land-uses, and assumed levels of technological advancement in agricultural production [28,29]. However, this approach only allows calculating the technical potential avoiding iLUC (i.e. the potential that is not limited by the demand for land for other uses [12]), while determining the economic potential (i.e. the fraction of the technical potential that could be produced at economically profitable levels) would be more informative in regard to the contribution of sustainable biofuels to energy supply systems.

Therefore, the goal of this paper is to present a land-use modelling framework combining empirical and theory-based land use modelling approaches to perform spatiotemporal assessments of land availability given the developments in other land-use functions, and determine the technical and economic potential of biofuel production avoiding iLUC. The proposed framework is exemplified with a case study on the development of land availability for bioenergy crops in Argentina up to 2030. Argentina has recently emerged as a key player in the biodiesel market due to the

implementation of differential taxes over different agro-industrialized products and governmental market-creating initiatives, taking advantage of favourable climate and soil conditions, low land and labour costs, and high quality existing infrastructure and human resources [30]. As a result, Argentina is currently the world's number one biodiesel exporter and production volumes are expected to keep increasing in following years [31].

2. Material and methods

2.1. Modelling framework

A schematic overview of the proposed land use modelling framework to determine availability of land and resulting technical and economic potential of biofuel production is depicted in Fig. 1. The availability of land for biofuel crops is accessed by assuming a “food first” paradigm, in order to avoid iLUC resulting from land competition between biofuels and food production. The future developments of land use for food and feed production are explored through dynamic land-use modelling. Food/feed-related land demand is assumed to be the main driver for occurrence of land-use change, which in turn depends on the development of underlying socio-economic factors: population growth, diet composition, exports, self-sufficiency ratio and productivity factors [14,29].

Proximate factors such as biophysical characteristics, infrastructure, and proximity to markets are considered to be the main allocation drivers of land-use change [16,32]. Allocation coefficients quantifying the relationship between the occurrence of dynamic land-uses (i.e. agricultural land-uses for food production) and the assumed allocation drivers are empirically calibrated through fitting of spatially-explicit data according to statistical analysis. The allocation of food-related land claims is then dynamically simulated, taking current land use as a starting point. Land constraints such as nature conservation policies and static land-uses (i.e. land-uses that are not allowed to be converted to agriculture) restrict the areas where dynamic land-uses are allowed to be allocated. The model output pinpoints future agricultural land use for food production, and the extension and spatial distribution of surplus land that it is not required to fulfill food demand, i.e. where biofuel crops could be cultivated without endangering food security. Accordingly, the technical potential for biofuel production avoiding iLUC is determined.

To determine the economic potential, it is then assumed that the available surplus land could be used for either biofuel production or additional food production, i.e. biofuel crops have to compete with other alternative agricultural land-uses for the available land. In the economic theory, the key concept in determining the allocation of land between competing land-uses and individuals is land rent, i.e. the economic return that is derived from land in its current use, after paying for total costs [33,34]. A spatially-explicit assessment of the economic performance of cultivating biofuel crops on the surplus land is therefore performed, to compare the profitability of alternative agricultural land-uses. This theory-based approach aims to reproduce the economic decisions of farmers and to simulate their willingness

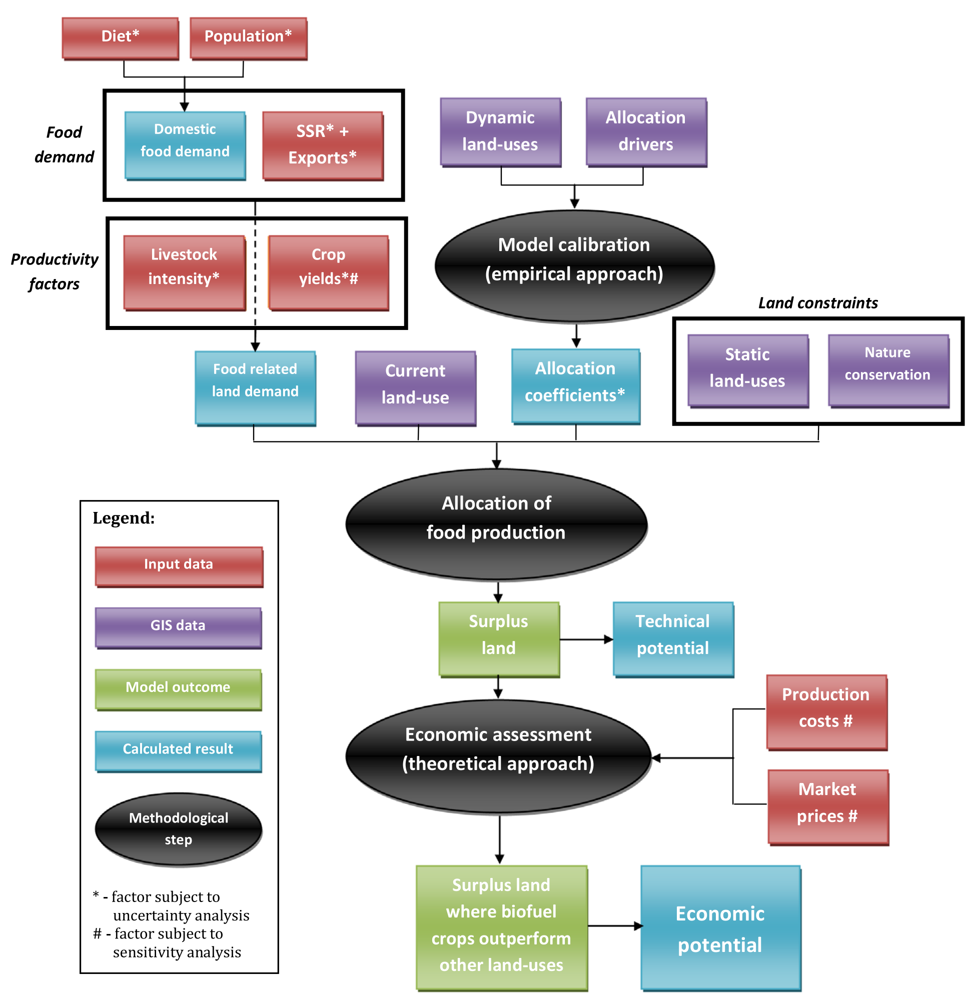

Fig. 1. Land use modelling framework to determine the economic potential for sustainable biofuel production.

to grow biofuel crops on the available surplus land. The economic potential for biofuel production is determined by identifying the surplus land locations where cultivation of biofuel crops outperforms other production options from an economic perspective.

The proposed framework involves three main methodological steps, which are discussed in more detail in the following subsections:

- Model calibration and validation.
- Determining food demand, allocation of food production and land availability.
- Economic assessment on the surplus land and biofuel potential.

2.1.1. Model calibration and validation

Logistic regression is the most commonly used method to calibrate land use models based on statistical analysis [35]. Logistic regression is a multivariate generalised linear model that allows predicting a discrete outcome from a set of explanatory factors. Because land-use change is usually represented as a discrete change from one land-use type to another, logistic regression is deemed as an appropriate statistical model to analyse and simulate this phenomenon [36]. When applying logistic regression to land-use change analysis and modelling, the dependent variable (i.e. land use) is categorical, with each category referring to a land-use type, while the assumed allocation drivers are considered as explanatory factors. GIS tools can be used to process spatial data as a regular grid and to overlay maps depicting land-use patterns and allocation drivers. The study area can be regarded as a statistical population in which each grid cell is an individual observation with certain attributes specific to its location. Logistic regression analysis allows to quantify the relation between the occurrence of a land-use type and a set of explanatory factors assumed to drive land-use allocation, by transforming the dependent variable into a logit variable as follows [35]:

$$\ln\left[\frac{P_{c,i}}{1-P_{c,\ i}}\right]=\beta_{0,i}+\beta_{1,i}X_{1,c}+\beta_{2,i}X_{2,c}+\cdots+\beta_{n,i}X_{n,c} \quad (1)$$

$P_{c,i}$ is the probability of land-use type i occurring in cell c, X_1–X_n are independent explanatory factors (that is, the assumed drivers), β_0 is a constant and $\beta_{1,i}$–$\beta_{n,i}$ are the logistic regression coefficients that indicate the direction (positive or negative correlation) and intensity of each explanatory factor on explaining the occurrence of land-use type i. These regression coefficients are estimated for each dynamic land-use type with a regular statistics software package through maximum likelihood. Accordingly, the model is calibrated and the allocation of food production is simulated.

The PCRaster Land Use Change (PLUC) model is used to simulate the allocation of food production and assess land availability in the study area up to 2030. It implements the PCRaster Python framework, which is a construction framework that offers a combined interface for geospatial analysis, spatiotemporal modelling and Monte Carlo analysis [28,44]. It is able to produce stochastic maps thus integrating simulation, uncertainty analysis and visualisation. A more detailed account on the PLUC model can be found elsewhere [28]. Land-use types are distinguished as dynamic, static or passive. Dynamic land-use types are those whose land claims are assumed to change in time and thus they are comprised by agricultural land-uses in which feed and food production takes place. Static land-cover types have no demand assigned and are assumed not to change. Passive land-cover types do not have demand assigned but are allowed to be converted to dynamic land-cover types.

Prior to simulating future land use, the model should however be validated. Validation is the process of measuring the agreement between the model output and independent data [21], aiming to inform the modeller about the level of trust one should put in the model, as well as the need to improve it. A common procedure to perform model validation is to use historical land-use data as the starting point for simulation and verify whether the model is able to reproduce current land-use patterns. A pixel-by-pixel comparison is performed to evaluate the model performance in terms of agreement between observed and predicted land-use change. Three maps are overlaid and compared: (1) a reference map of the initial time; (2) a reference map of the subsequent time; (3) a prediction map of the subsequent time. Accordingly, the level of agreement between observed and simulated land-use change patterns is assessed by determining the three statistic measures proposed by Pontius et al. [37]: figure of merit, producer's accuracy and user's accuracy. However, these indicators are only able to assess the ability of the model to predict land-use change [38] and therefore indicators measuring the ability to correctly predict persistence and the overall performance of the model are also estimated:

$$\text{Well predicted persistence}=E/(D+E) \quad (2)$$

$$\text{Model performance}=(B+E)/(A+B+C+D+E) \quad (3)$$

where A – area of error due to observed change predicted as persistence, B – area of correct due to observed change predicted as change, C – area of error due to observed change predicted as wrong gaining category, D – area of error due to observed persistence predicted as change, and E – area of correct due to observed persistence predicted as persistence.

2.1.2. Determining food demand, allocation of food production and land availability

To determine food/feed demand and related land claims, the following factors are considered [14,29]:

– population and diet composition, which determine domestic food demand;
– exports and self-sufficiency ratio (SSR, i.e. the part of domestic food demand that is produced within the study area), which jointly determine the net food demand in the study area;
– productivity factors, specifically locally attainable crop yields and livestock intensity, which determine the food/feed-related land demand to accommodate food production.

The demand for vegetal and animal products is analysed separately [12–14,29]. Different types of animal production systems are considered, each type of system accounting for a specific feed composition, production efficiency and share on the total production of animal products according to an assumed advancement level of technology. The demand for animal products and feed composition determines the demand for feed grass from pastures and food crops used for feed purposes. Finally, the demand for feed is added up to the demand for vegetal products resulting from domestic human consumption and exports, thus giving the total demand for food/feed crops. A more detailed account on the methodology to determine the demand for crops and grass can be found elsewhere [12]. The model then translates food and feed demand into land claims according to the attainable crop yields. Locally attainable yields are spatial-explicitly represented in the model through yield reduction maps depicting for crops and grass what fraction of the maximum attainable yield could be locally reached, considering a maximum attainable yield for each crop according to the assumed level of technological advancement.

Since developments in socio-economic and technological factors determining land claims for food production are highly uncertain [39], different scenarios are considered in order to

explore possible future alternatives. The use of scenarios is a popular approach to identify policy alternatives and assess possible future developments of complex systems such as land use systems [21]. Rather than predictions, they are an approach to help managing decisions based on the interpretation of qualitative descriptions of alternative futures translated into quantitative scenarios [40].

Furthermore, input data such as model parameters and spatially-explicit datasets are fraught by errors that propagate through the model because the state of the modelled system at a certain time step is a function of previous states, thus generating uncertainty in the model outputs [28]. Therefore, input errors are also taken into account by calculating the forecast uncertainty through Monte Carlo analysis, in which allocation drivers, productivity and socio-economic factors are represented stochastically. An account on the implementation of the Monte Carlo analysis in the PLUC model framework can be found in Verstegen et al. [28].

2.1.3. Economic assessment on the surplus land and biofuel potential

According to Alonso's bid rent theory [34], land-users seek to maximise utility or profit and, in a competitive land market, land is purchased/rented by the bidder offering the highest bid. It is therefore assumed that land is used for the purpose that brings the greatest benefits to the owner. Farmers can choose among different crops, taking into account different locally attainable yields, selling prices, and transportation and production costs. However, the possibility of growing different crops is usually constrained by local biophysical factors such as soil and climate characteristics. The net present value (NPV) is a standard method to appraise long-term projects, by measuring discounted time series of expected cash flows. When applying this method to land-use decision-making, NPV is determined in the following way:

$$\mathrm{NPV}_{c,i} = \sum_{t=y}^{n} \frac{B_{c,i,t} - C_{c,i,t}}{(1+r)^{t-y}} \tag{4}$$

where $\mathrm{NPV}_{c,i}$ is the net present value derived from land-use i in land parcel c in the reference year, $B_{c,i,t}$ and $C_{c,i,t}$ are respectively the benefits and the costs of land-use i in land parcel c in year t, r is the discount rate, y is the initial year of the project and n–y is the lifetime of the project. According to the bid–rent theory, it is assumed that the farmer will select the land-use (i.e. production system) providing the highest NPV. Thus the economic performance of biofuel crops on the surplus land is assessed by comparing the NPVs of different production systems in each land parcel. For any land parcel, if biofuel crop's NPV is positive and higher than all other alternative production systems, it will be considered as potentially viable for biofuel crop production.

The economic performance of biofuel and food production systems appears to be quite sensitive to variations in production costs, crop yields and market prices [17]. Therefore, a sensitivity analysis on the economic performance of the considered production systems is conducted to quantify the impact of the variability in these factors on the biofuel potential.

2.2. Case study in Argentina

The framework presented in Section 2.1 was applied to a case study in Argentina. Argentina is a large country in which 6 large eco-regions can be identified, each one accounting for completely distinct climatologic, topographic and landscape features [41]. Consequently, agricultural production systems are extremely variable along the country, with more than 100 different homogeneous agroeconomic zones (HAZ) identified according to their environmental and socio-economic characteristics [42]. Therefore, the study area was confined to the eco-regions of Region Pampeana and Chaco (Fig. 2), which jointly account for more than 90% of the total production and total area required to produce food commodities, 80% of total cattle herd and almost 100% of total milk production in Argentina [43]. Limiting the simulation area to these eco-regions allowed focusing on the most relevant agricultural production systems and avoiding computational issues resulting from dealing with large datasets.

The main methodological steps for the implementation of the proposed framework in the case study in Argentina are described in the following sub-sections, namely the calibration and validation of the land-use model (Section 2.2.1), the determination of food demand and allocation of food production in the study region (Section 2.2.2.) and the economic assessment on surplus land (Section 2.2.3).

2.2.1. Model calibration and validation

A model application previously applied in a comparable case study in Mozambique [29] was adapted to fit the characteristics of the study area. The agricultural sector in Argentina is relatively developed and directed mainly towards international markets [45], thus being quite distinct from Mozambique. Therefore, some adjustments were made in order to fit the model to the Argentinean case study by (1) designing a land-use typology according to

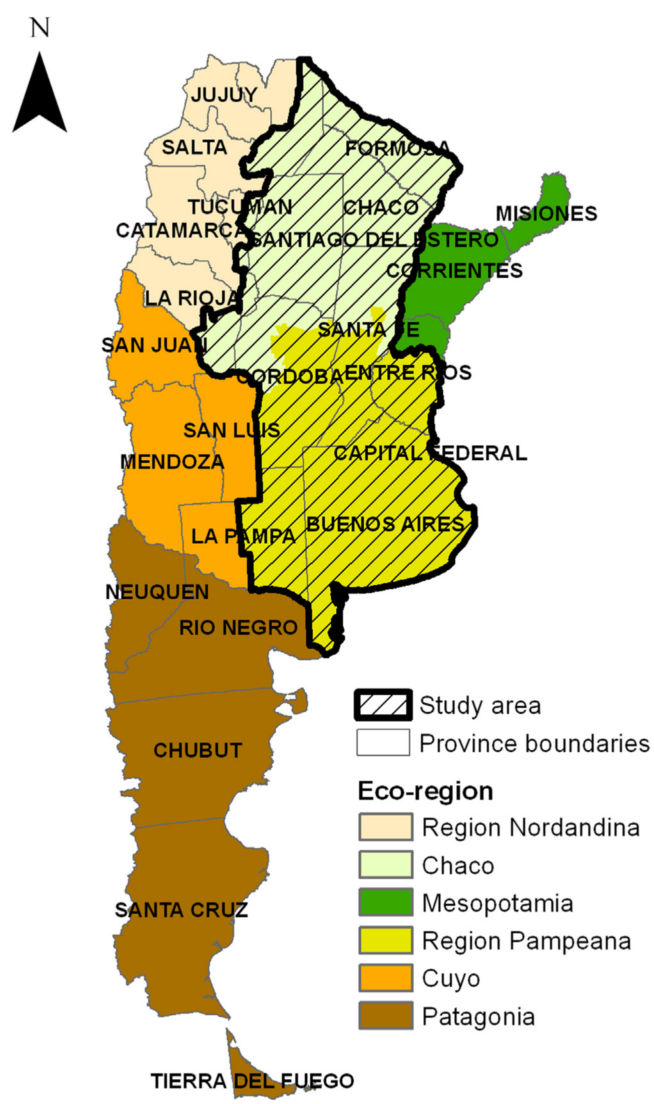

Fig. 2. Eco-regions in Argentina and selected study area.

the production systems existing in the study area; (2) identifying the most important allocation drivers operating in the study area. Data sources of spatially-explicit data on land use and allocation drivers are documented as Supplement material in Appendix A. A more extensive discussion on the adaptation of the model is provided in Appendix B.

The considered land-use typology and allocation drivers are summarised in Table 1. Five main types of production system were considered (see Appendix B.1): two mixed rotation systems involving the rotation of livestock production and annual crops; two pure agricultural rotation systems, involving the rotation of annual crops; and a livestock production system, in which land is solely used for extensive livestock grazing. Even though built-up areas are expected to expand due to population growth, the development of new urban areas at national level is often relatively low when comparing to the total area of the country [46]. Therefore built-up areas were considered as a static land-use.

Logistic regression analysis was performed for each dynamic land-use type to calibrate the coefficients indicating the direction and intensity of the assumed allocation drivers on explaining the occurrence of that land-use type. The forward selection method based on likelihood ratio was applied. The stepwise selection of explanatory variables is based on the significance of the score statistic, and removal testing is based on the probability of a likelihood-ratio statistic according to the maximum partial likelihood estimates. The explanatory variables that did not appear to be statistically significant and/or were strongly correlated with other variables were removed from the analysis.

A model validation was then performed by simulating land-use in the period 2005–2009. Demand for food products and maximum attainable yields was determined according to the recorded statistics on production and yields for each year during that period. Accordingly, land use was simulated for this time frame using 2005's land-use map as a starting point. The simulated land-use patterns were then compared with the ones observed during the same period. Only dynamic land-use classes were evaluated while performing the model validation.

2.2.2. *Determining food demand, allocation of food production and land availability*

The allocation of food production systems and land requirements to meet the demand for food crops and grass was simulated in yearly time steps up to 2030. Two main storylines were taken into account to explore future developments on technology adoption in the agricultural sector and their impact on land availability: (1) Business-As-Usual (BAU) scenario, in which large-scale production of bioenergy is implemented without major changes in policies, technology adoption and managerial practices; (2) Progressive scenario (PS), in which stable policy frameworks are implemented to promote adoption of technology and advanced practices, resulting in increasing productivity, i.e. higher crop yields and more efficient feed conversion, in comparison with the BAU scenario. Similarly to a previous spatially-explicit assessment of biofuel potential [29] socio-economic drivers such as population growth, level of affluence, diet, exports and self-sufficiency ratio were not subject to scenario variation, in order to allow for a more transparent comparison among scenarios. Though these factors change over the simulated time frame, the rate of change is the same among scenarios. Consequently, food demand is also the same, but land claimed for food production may differ substantially according to the scenario, due to changes in feed composition and productivity. The distribution of the total food crops demand among the considered agricultural and mixed production systems was determined by assuming that the trends observed in the last decade would be maintained over the considered time frame. A comprehensive discussion on the socio-economic drivers and scenario-dependent variables used in scenario analysis is provided in Appendix C.

Input errors were taken into account by calculating the forecast uncertainty through the Monte Carlo analysis, determining the probability, relative error and variance of land becoming available for biofuel production. The model was run according to the Monte Carlo analysis configuration using 500 samples. The following factors were stochastically modelled in the Monte Carlo analysis: food consumption per capita, population growth, exports, maximum attainable yields, feed conversion efficiency and spatially-explicit allocation drivers (a more detailed discussion is provided in Appendix D).

2.2.3. *Economic assessment on surplus land and biofuel potential*

A spatially-explicit assessment of the economic performance of growing biofuel crops on the surplus land in comparison with the considered agricultural, mixed and livestock production systems (see Table 1) was performed. In this case study, the potential for first and second generation biofuels was distinguished. Soybean biodiesel production was used as a case study for first generation biofuel. Soybean production chain is a crucial sector in the Argentinean economy, accounting for 25% of currency income of the country and 31% of the internal agro-industrial product. Soy biodiesel is regarded as the most important biofuel option in Argentina due to two main reasons given as follows: (1) diesel is currently the main transportation fuel in Argentina, thus making soybean biodiesel a suitable option for the internal market to reduce diesel imports and supply vulnerability; (2) a robust industrial park for vegetable oil production and advanced agricultural sector already exist. A more detailed account on the recent developments of soy agro-industrial complex and biofuel policy in Argentina can be found elsewhere [47–49].

The potential for soybean biodiesel production was addressed in a specific way, since soy is not a traditional dedicated energy crop but rather a food/feed crop from which only a by-product is used for energy purposes [47]. This implies that the demand for other soy products (specifically, soymeal and soyoil) has also to be explicitly taken into account in order to determine the total potential for soybean biodiesel. The potential for biofuel resulting from the existing soy production chain is therefore determined by assuming that the oil resulting from soymeal production not required to fulfill the demand for soyoil is further processed to

Table 1
Land-use typology designed for the study region and allocation drivers operating in the agricultural and livestock production sectors in Argentina.

Dynamic land-use types	*Passive land-use types*	*Static land-use types*	*Allocation drivers*
• Mixed rotation 1 • Mixed rotation 2 • Agricultural rotation 3 • Agricultural rotation 4 • Livestock production	• Forest • Sparse vegetation • Mosaic forest/shrubland	• Bare areas • Water bodies • Permanent snow and ice • Built-up areas • (Semi-)permanently flooded vegetation	• Biophysical suitability for crops/pastures • Distance to main markets and ports • Distance to cities and villages • Distance to water bodies • Neighbourhood relationships

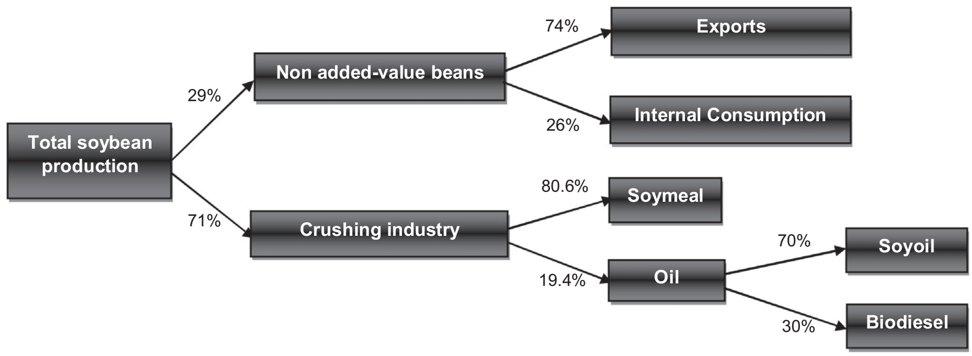

Fig. 3. Product share in current soy complex in Argentina (based in Hilbert et al. [51]).

biodiesel. Since projections up to 2030 do not specify the final use of soybeans [50], it is assumed that the current shares of the production chain are maintained [51] (see Fig. 3).

Furthermore, the increase in the use of soymeal as feed for livestock production assumed in PS scenario (see Appendix C) is considered to lead to an increase in the biofuel potential. The reasoning for this is that, since the demand for soyoil is already fulfilled (as in BAU scenario), the additional vegetable oil resulting from bean crushing to produce the additional soymeal feed could be fully converted to biodiesel.

Switchgrass has been studied as a potentially attractive bioenergy crop in Argentina [13] and it is taken into consideration as a second generation biofuel alternative. Despite the limited experience in commercial exploitation in Argentina [52], potentially high yields and high content of cellulose and hemi-cellulose make switchgrass an appealing alternative for biofuel production [53].

Input data for the economic assessment and biofuel conversion factors are described in Appendix E.

3. Results

3.1. Model calibration and validation

A detailed account on the results of the model calibration and validation can be found in Appendix B.3. Coefficients indicating the direction and intensity of a set of allocation drivers in explaining land use were estimated for each dynamic land-use type. Neighbourhood relationships appeared to be the driver with the strongest explanatory power for all productions systems, thus reflecting the role of positive spatial autocorrelation in agricultural land-use patterns. Very strong fitness was obtained for the regression models of mixed and agricultural rotations. Though still reasonably good, the obtained fitness for the regression model of livestock production was slightly weaker. This can be explained by the existence of various agro-ecological livestock regions in Argentina and the fact that livestock production was not differentiated in different production systems (e.g. meat and milk production).

A model validation was performed by determining a number of indicators assessing the model performance in reproducing observed land-use patterns. It can be concluded that model has a good overall performance, with roughly 91% of land-use correctly allocated in the study area. In particular, the model has a very good ability to correctly predict persistence of land-use (95%). However, the model does not perform so well on allocating land-use change, possibly due to the low rate of land-use change in relation to the total extent of the study area. Furthermore, this analysis is based on a pixel-by-pixel comparison, which is not suitable to distinguish whether the model is allocating the correct land-use in the surroundings but not exactly in the correct cells or in totally disparate locations. After repeating the validation using a coarser resolution, land-use change indicators appeared to improve, leading to the conclusion that even though land-use change is not perfectly allocated, the model is able of producing fairly sensible land-use patterns of agricultural land use.

3.2. Determining future demand, allocation of food production and land availability

Future demand for food crops is projected to grow in both scenarios, not only due to population growth and increasing exports but also as a result of the increase on the demand for animal products, and consequently on the overall demand for feed. The demand for food crops is slightly higher in the PS scenario, due to higher demand for feed crops (Fig. 4) resulting from the shift of livestock production from pastoral to intensive landless systems and underlying changes in feed composition. In the BAU scenario, the overall feed demand increases in time, following the increase on the demand for animal products. In the PS scenario, the overall feed demand is lower than in the BAU scenario, due to an increase on the feed conversion efficiency. Moreover, while in the BAU scenario feed demand for grass increases due to the increase of demand for animal products, in the PS scenario it is projected to decrease, following the change in feed composition.

The net land-use changes occurring between 2009 and 2030 according to the BAU scenario and the resulting land-use system in 2030 are depicted in Fig. 5. The currently observed trends of land-use change are maintained during the considered time frame as follows: (1) mixed production systems are gradually substituted by pure agricultural systems in the provinces of Buenos Aires and La Pampa [54]; (2) the share of soy in the agricultural rotation schemes increases in the provinces of Buenos Aires, Santa Fe and Cordoba [55–57]; (3) pastoral systems for livestock production keep expanding at the expense of nature areas, particularly in previously forest-covered areas of Chaco eco-region [57–59].

Since technological developments in crop production and particularly in livestock production are modest in the BAU scenario, the increase in demand for food commodities results in the expansion of land area required to supply food demand and therefore no surplus land is expected to become available in 2030 (Fig. 6). In contrast, the increase in feed conversion efficiency and use of feed crops in the food composition assumed in the PS scenario result in lower land area requirements for livestock production in pastoral grazing systems, despite the increase in the demand for animal products. Moreover, even though there is an increase in the use of food crops for feed, the total area of land devoted to agriculture and mixed rotation systems remains fairly constant during the considered timeframe due to the increase in attainable crop yields. Consequently, around 32.6 Mha could

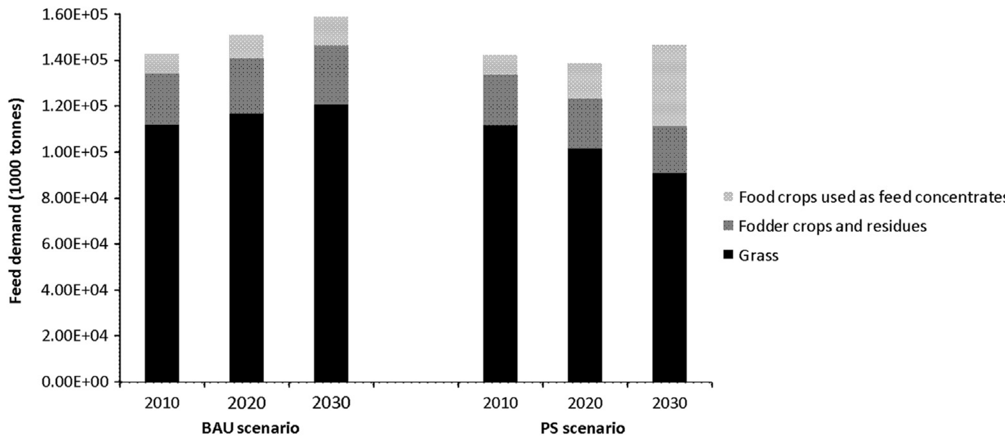

Fig. 4. Feed demand in 2010, 2020 and 2030 in BAU and PS scenarios.

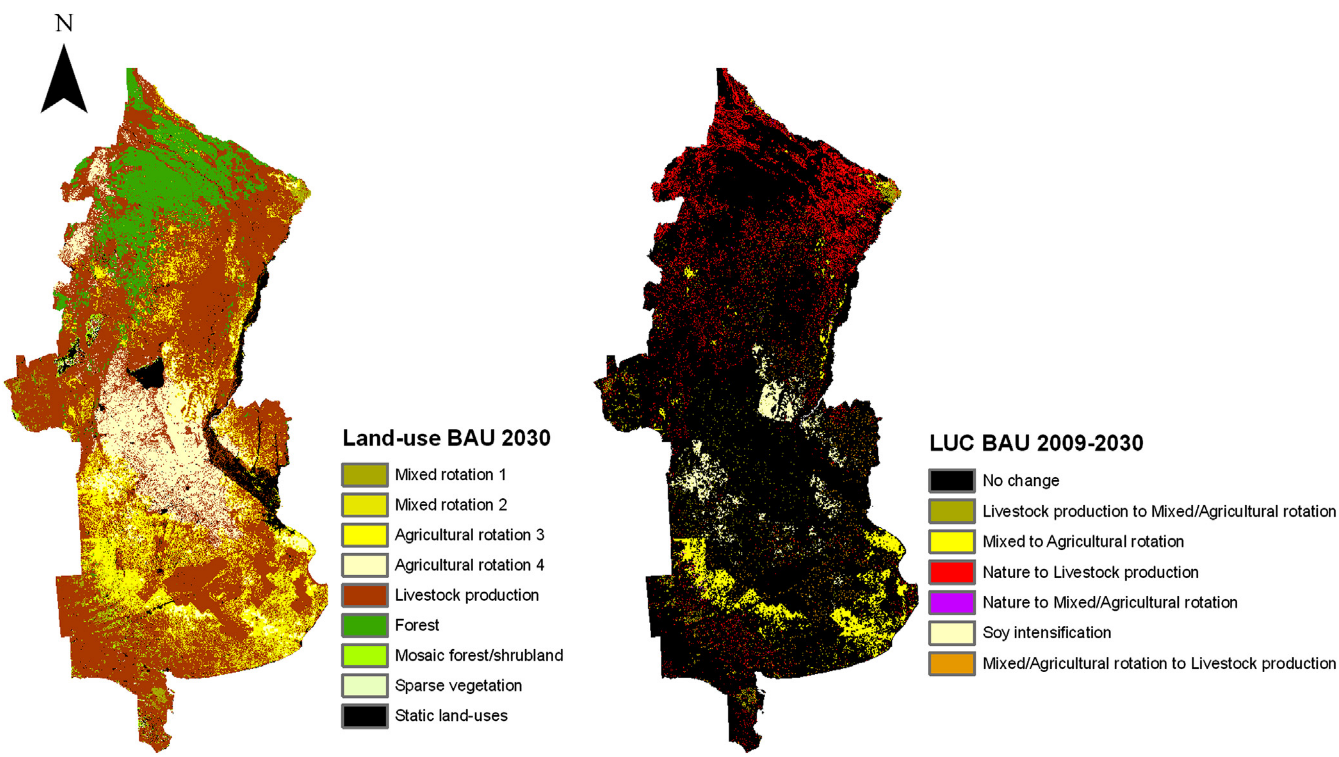

Fig. 5. Land use in 2030 BAU scenario (left) and resulting land-use change 2009–2030 (right).

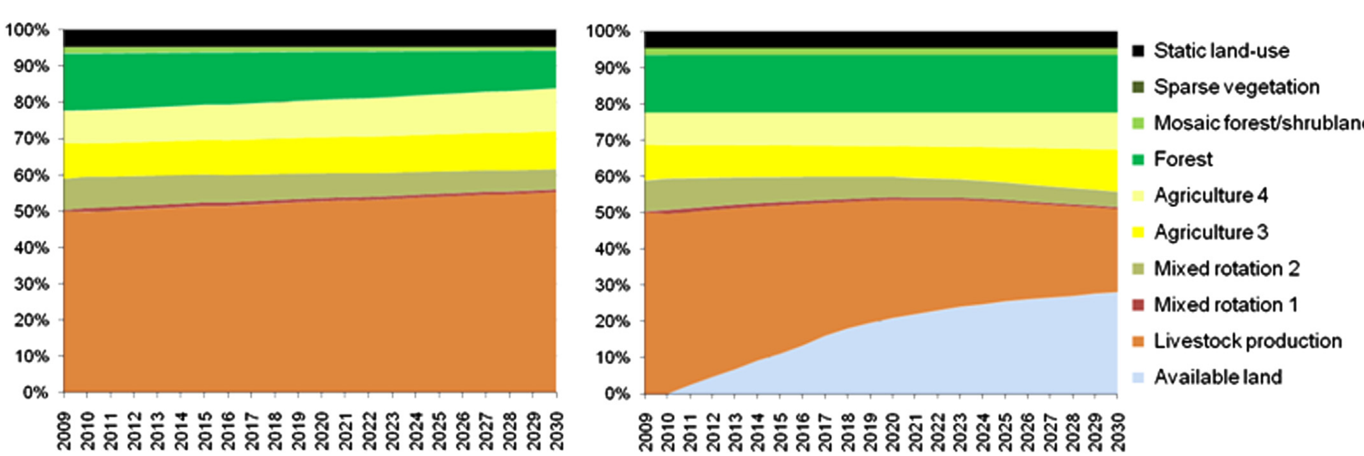

Fig. 6. Land-use during 2009–2030 according to BAU (left) and PS (right) scenarios.

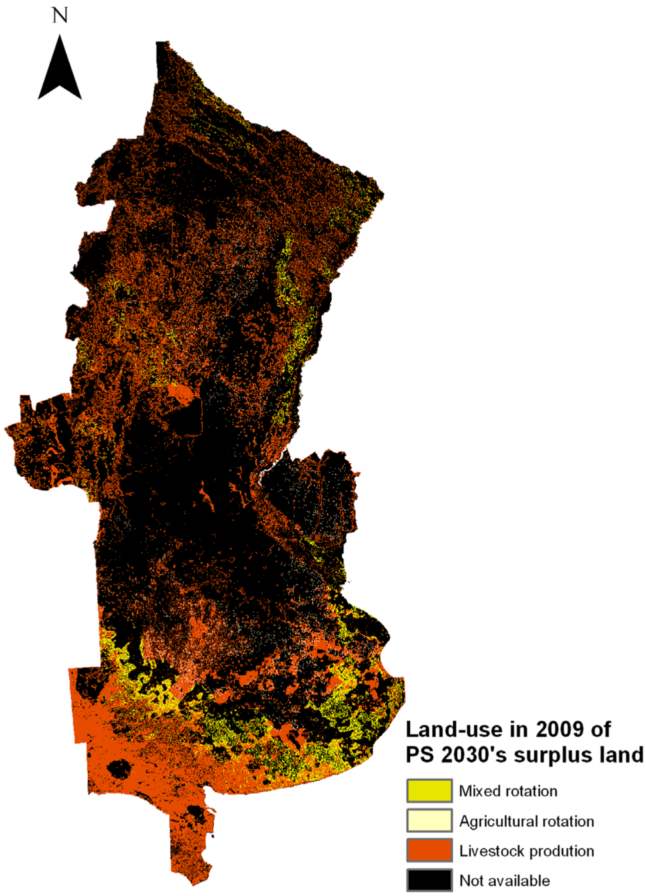

Fig. 7. Previous land-use of surplus land in 2030 according to PS scenario.

become available for dedicated biofuel production by 2030. Since the area required for livestock production decreases, the conversion of nature areas to pastoral grazing systems observed in the BAU scenario does not occur in the PS scenario.

Fig. 7 also shows that, according to the PS scenario, the largest share of surplus land available by 2030 is currently used for livestock production in pastoral systems (82.3%), followed by mixed production systems (15.0%) and agriculture (2.7%). A large part of surplus land is located in the south-eastern part of the Buenos Aires province and in the La Pampa province, where the biophysical suitability for conventional annual crops is low. The most productive regions in the centre of the country are used for food crop production and thus are not available for dedicated cultivation of energy crops.

The results of the Monte Carlo analysis for the BAU and PS scenarios are shown in Fig. 8, which depicts the probability of land being available for biofuel production in 2030. It can be seen that even when taking into account the uncertainty on demand and productivity, the probability of having land available for biofuels in the BAU scenario is low. The regions that still hold a slightly higher probability resemble to some extent those that appeared to be available in the PS scenario's deterministic simulation. Nevertheless, even in these areas the probability of land becoming available never exceeds 30%.

Regarding the PS scenario, comparable spatial patterns can be identified, but with a higher probability. La Pampa and southwest Buenos Aires provinces account for a large area with high probability of becoming available for biofuel crops. The northern regions also present areas with high probability, but here the patterns seem more scattered. On the other hand, the most fertile soils in the centre of the study area, the grasslands in the centre of Buenos Aires provinces and Chaco ecosystem seem very unlikely to become available.

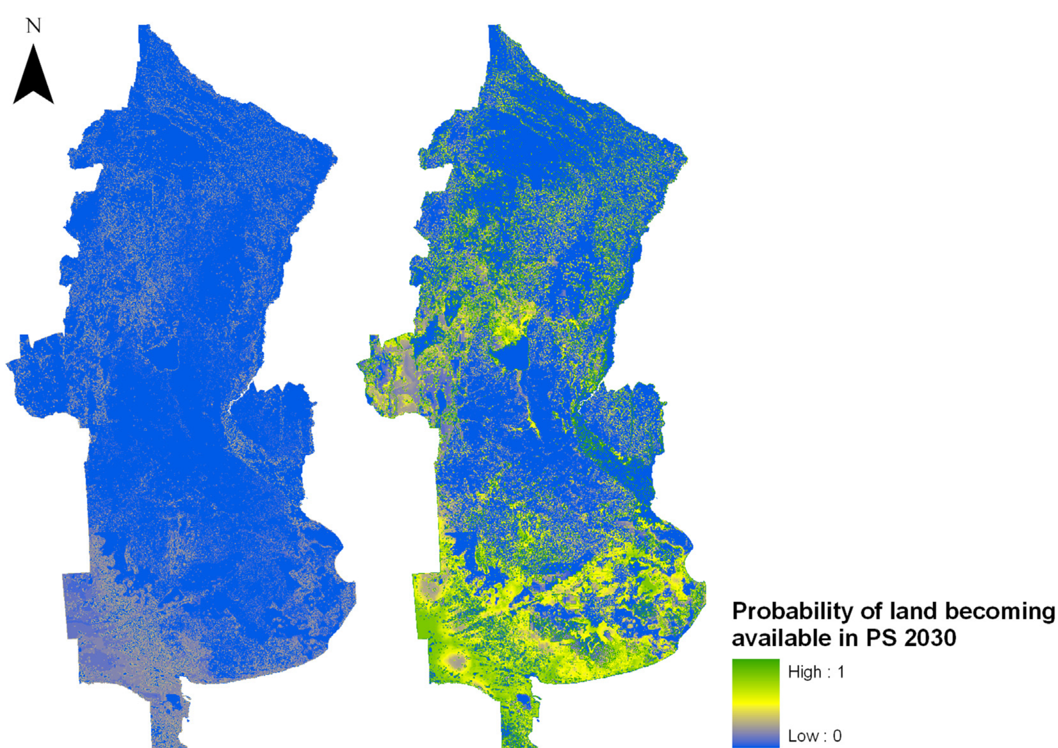

Fig. 8. Monte Carlo analysis of 2009–2030 period and resulting probability of land becoming available in 2030 for the BAU (left) and PS (right) scenarios.

The uncertainty analysis underpins the previous results identifying the pastoral areas in La Pampa and southwest Buenos Aires provinces as regions potentially suitable for large-scale biofuel production, in terms of land availability. It also shows that the uncertainty on the most important suitability factors does not seem to significantly affect the spatial patterns of land availability. The uncertainty on total food demand and factors related to technology development (particularly, feed conversion efficiency and the proportion of intensive systems in bovine meat production) seems to play an important role on the extent to which land may become available in the future. It can be concluded that if current trends of technology adoption are maintained, land is unlikely to become available for biofuel crops. It also showed that even though there is a large potential for land becoming available in case of higher rate of technology adoption, the availability of land for biofuel crops will still largely depend on the future development of food demand.

3.3. Economic assessment on surplus land and biofuel potential

Following the simulation of future land-use according to the PS scenario, Fig. 9 depicts the economic performance of soybean and switchgrass on the available surplus land in 2030 compared to the considered agricultural, mixed and livestock production systems. The locations with negative values (green) are those in which biofuel crops outcompete the competing food production systems, while in locations with positive values (red) biofuel crops are outcompeted by at least one of them. Switchgrass appears to be the most attractive production system from an economic point of view in 15.1 Mha, i.e. 46.7% of the total surplus land. Switchgrass appears to particularly outperform all competing production systems on the region of southwest Buenos Aires and La Pampa provinces. This is explained by the fact that biophysical suitability for conventional annual crops is relatively low in this region but not for switchgrass.

Soybean cultivation totally dedicated to biofuel production is the most attractive option in 4.2 Mha, i.e. around 13% of total surplus land available for biofuel production. In addition, soy cultivation is found to be economically attractive as part of crop rotation schemes including other crops, namely *Agricultural rotations 3* and *4*. In fact, these production systems showed to be the most attractive option in 0.6 and 4 Mha of the available surplus land, respectively (Fig. 10).

A sensitivity analysis on the economic performance of the production systems was performed in order to assess the sensitivity of the NPV to changes in key factors. The sensitivity analysis of soy and switchgrass (Figs. 11 and 12) performance when biophysical suitability is optimal (i.e. yield reduction is 0%) is shown below as an example. It can be concluded that the economic performance of both crops is most sensitive to changes in maximum yields and market prices. Variations on the discount rate also appeared to have a significant effect on NPV, especially for switchgrass, due to its initial investment costs and long-term project profile.

Fig. 13 illustrates spatially-explicitly the sensitivity of the economic performance of soy and switchgrass cultivation to variations in their market prices, the factor to which NPV appeared to be most sensitive. It could be observed that if soy market prices increased by 50% compared to current prices, soy cultivation would be able to outperform other options in an area of 12.4 Mha, particularly in the southwest of the study area.

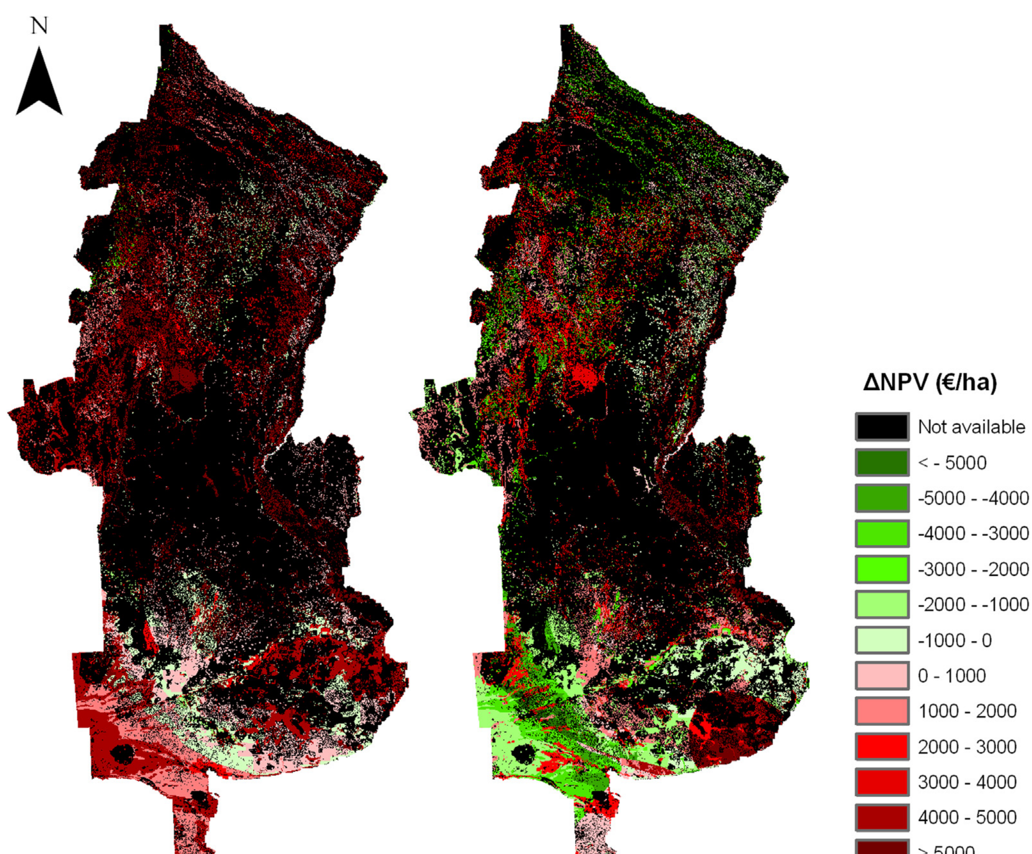

Fig. 9. Economic assessment on available surplus land in 2030: maximum attainable NPV of the considered production systems minus the NPV of dedicated biofuel crop cultivation, soy (left) and switchgrass (right). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

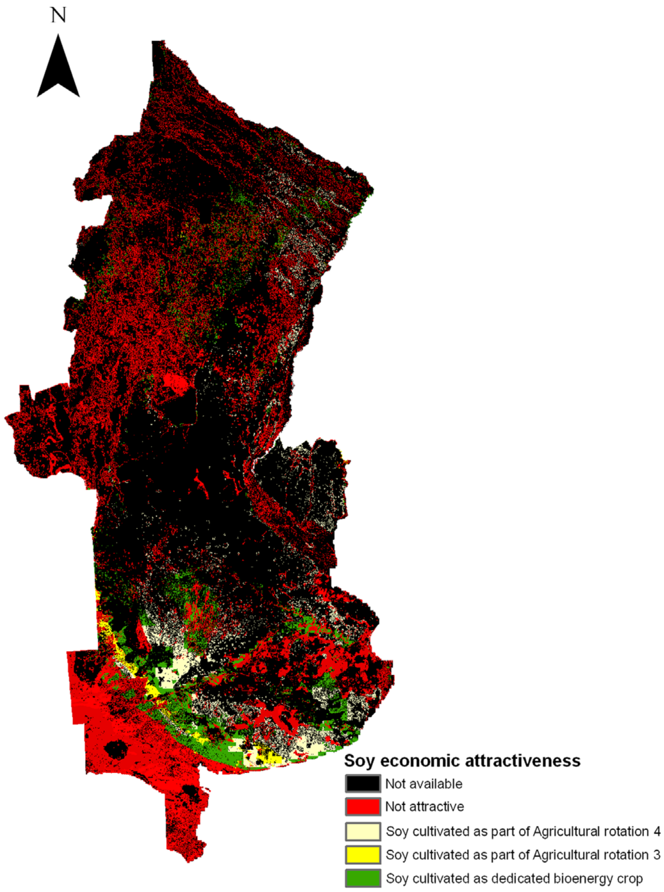

Fig. 10. Economic attractiveness of soy cultivated on surplus land as part of different crop rotation schemes.

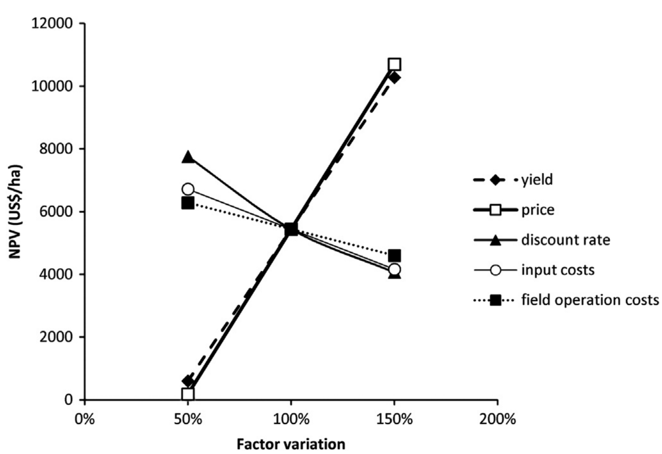

Fig. 11. Sensitivity analysis on the economic performance of soy cultivation (excluding transportation and land costs, which are location dependent).

However, if soy prices decreased by 50%, it would be outperformed by all competing production systems. It can also be concluded that even if the assumed price for switchgrass decreases by 50%, switchgrass would still outperform the other production systems in 4.9 Mha, particularly in a large area of La Pampa and Buenos Aires provinces. In case switchgrass price increased by 50%, it would become the most attractive production system in an additional area of 19.9 Mha.

Table 2 summarises the results regarding the technical and economic potential for biofuel production from soy and switchgrass in Argentina by 2030. According to the dynamic simulation of future land use following the BAU scenario assumptions, no surplus land is expected to become available for biofuel production by 2030. Therefore, there is no potential for the production of switchgrass ethanol in this scenario. However, the existing soy complex for soymeal feed production is expected to keep growing. Soybean-based biodiesel is produced through conversion of oil resulting as a by-product of soybean crushing for soymeal production. Hence, taking into account the expected demand for soybeans, soymeal and soyoil (see Fig. 3), a technical and economic potential of 103 PJ[1] soybean biodiesel could be achieved by 2030. According to PS scenario, an additional demand for soybeans is expected (8.5×10^6 odt) in this scenario, due to the increase of soymeal in the feed composition for livestock production. This could provide an additional potential of 60 PJ, leading to a total potential of 163 PJ produced as a by-product of soymeal feed production. In addition, 32 Mha of surplus land could become available for dedicated soybean cultivation (44×10^6 odt), leading to a potential production of 309 PJ. Therefore, an overall technical potential of 472 PJ soybean biodiesel could be obtained by 2030. However, soybean cultivation appeared to be economically competitive in only a portion of the available surplus land. Taking into account the locally specific yields and the proportion of soy in each production system, a soybean production of 34×10^6 odt could be attained on the surplus land, which after conversion to biodiesel could lead to a potential of 205 PJ. Taking into account the existing soy complex for feed production, a total economic potential of 368 PJ soybean biodiesel could be attained by 2030.

A production volume of 170×10^6 odt switchgrass could be attained in the available surplus land in the PS scenario, leading to a technical potential of 1.4 EJ switchgrass-based ethanol production. The economic assessment on the surplus land also showed that switchgrass could become an economically attractive crop in a large portion of the available surplus land. Considering the locally specific yields, an economic potential of 1.1 EJ bioethanol could be expected in 2030, through the conversion of 124×10^6 odt switchgrass.

Figs. 14 and 15 compare the cost–supply curves of the technical and the economic potential for soy and switchgrass cultivation on the surplus land. It can be seen that most part of economic and theoretical potential of soy could be obtained at a feedstock production cost level between 100 and 155 US$/ton. The feedstock

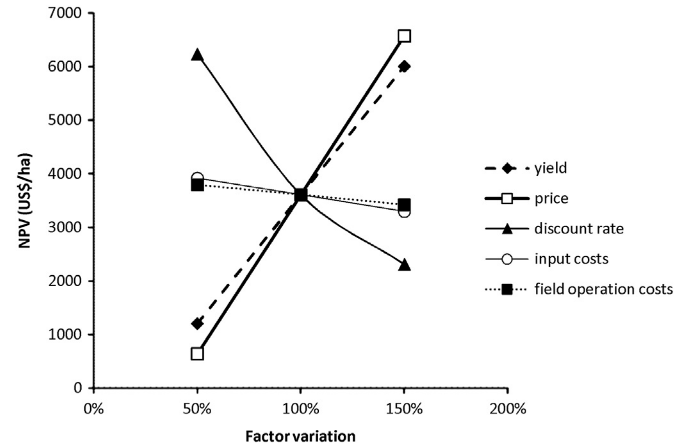

Fig. 12. Sensitivity analysis on the economic performance of switchgrass cultivation (excluding transportation and land costs, which are location dependent).

[1] The joule (J) is a derived unit of energy in the International System of Units, being 1 J equal to the energy expended in applying a force of 1 N through a distance of 1 m. Joule is typically used on statistic records of primary energy use. E.g. The Netherlands has a primary energy use over 3000 PJ (i.e. 3000×10^{15} J) per year.

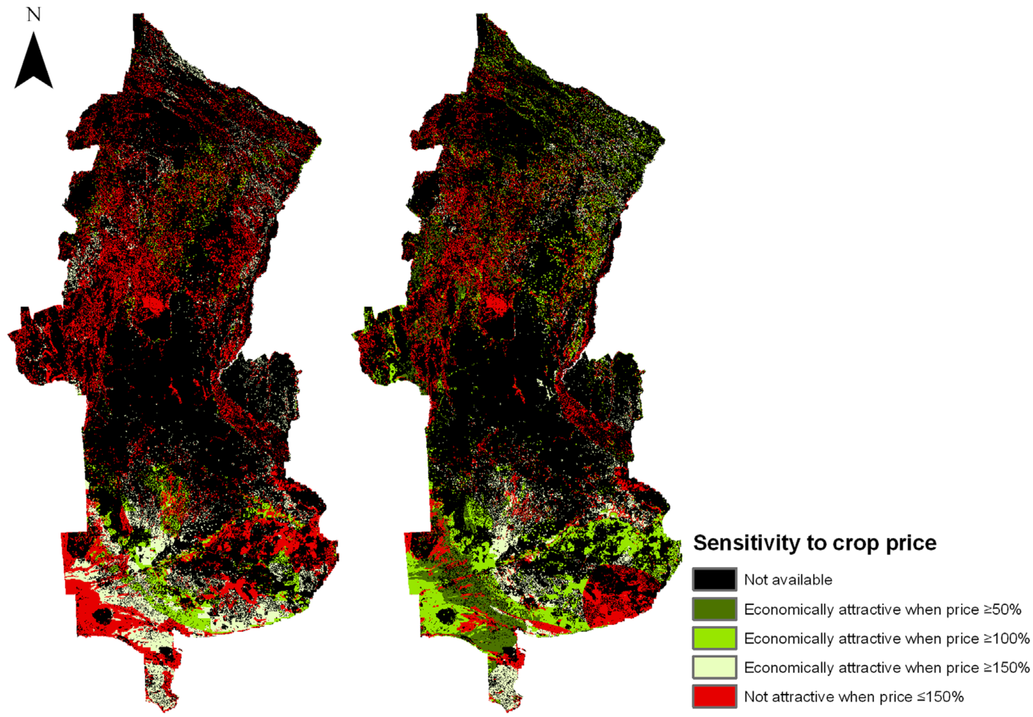

Fig. 13. Spatially-explicit sensitivity analysis on the economic performance of soy (left) and switchgrass (right) cultivation to variations in market crop price.

Table 2
Technical and economic potential of soybean biodiesel and switchgrass ethanol production (in $PJ_{biofuel}$) in Argentina in 2030 for the BAU and the PS scenarios.

Crop	Type of potential	Scenario	
		BAU	*PS*
Soy	By-product of feed production	103	163
	Production on available surplus land	–	309
	Economically competitive production on surplus land	–	205
	Technical potential	103	472
	Economic potential	103	368
Switchgrass	Technical potential	–	1445
	Economic potential	–	1058

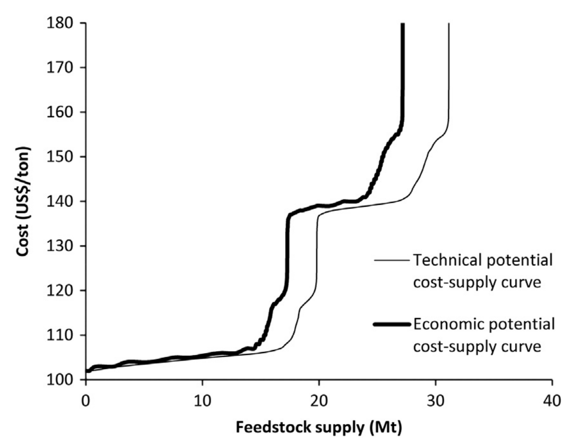

Fig. 14. Cost–supply curve of the technical and economic potential of soy cultivation given the land availability in 2030 in the PS scenario.

production costs of switchgrass range between 20 and 45 US$/ton. Switchgrass production costs per unit of mass are much lower than for soy due to higher attainable yields, less input and field operation requirements and high attainable yields in locations with low land rental prices.

The results demonstrate that the economic potential of biofuel crops can vary considerably and be largely affected by variations in land availability, crop market prices, attainable yields and production costs. Therefore, two cases were designed to explore ranges of variation of biofuel potential, by combining the results of sensitivity and uncertainty analyses in 2030 as follows:

- pessimistic-case: surplus land becomes available only in areas where the probability is higher than 75% and biofuel crop market price is 50% lower than previously assumed;
- optimistic-case: surplus land becomes available in all areas where probability is higher 50% and biofuel crop market price is 50% higher than assumed.

According to the pessimistic-case, it was found that soy cultivation would not be economically viable in the entire surplus land. Therefore the potential in 2030 would be only the biodiesel resulting as a by-product of feed production. Switchgrass would be economically attractive in only 1.4 Mha, leading to a biofuel potential of 87 PJ. According to the optimistic-case, the potential for soy biodiesel production in the surplus land would amount to 209 PJ, leading to a total economic potential of 372 PJ; switchgrass would be viable in 17 Mha, allowing for the production of 1.2 EJ bioethanol. Fig. 16 depicts the results on technical and economic biofuel potential in Argentina by 2030, and possible ranges of variation according to the proposed pessimistic- and optimistic-cases. It can be seen that the potential of switchgrass ethanol in 2030 is generally much higher than soybean biodiesel, but the ranges of variation are also much larger. When comparing the potentials following the pessimistic-case, the economic potential of switchgrass ethanol is actually lower than soybean biodiesel. This stems from the fact that soybean biodiesel production makes part of an already well-established production chain within the agro-industrial sector in Argentina. Therefore, economic potential of soybean biodiesel is not as sensitive to future developments as switchgrass ethanol, of which large-scale production in Argentina

will largely depend on developments in land availability and market conditions.

4. Discussion

4.1. Methods and input data

The availability of surplus land for biofuel crops was assessed through dynamic land-use modelling using statistical analysis to calibrate the allocation module. The model validation demonstrated that the model is able to replicate the main currently observed agricultural land-use patterns. Despite being able to simulate land allocation of agricultural production systems with different characteristics, the proposed modelling approach is not able to explicitly explore developments on structural changes at the local level. For that purpose, agent-based models are better suited to simulate socio-economic processes such as farm structure change and concentration of production and land. For instance, Bert et al. [56] was able to reproduce the major ongoing patterns in Pampas region resulting from differences among farmers' ability to generate agricultural income, namely (1) fewer farmers operating larger areas, (2) an increase in the area operated by tenants and (3) an increase in the area cultivated with soybean. The combination of different modelling approaches could thus allow studying the outcomes of different driving forces operating at several levels in the land-use system.

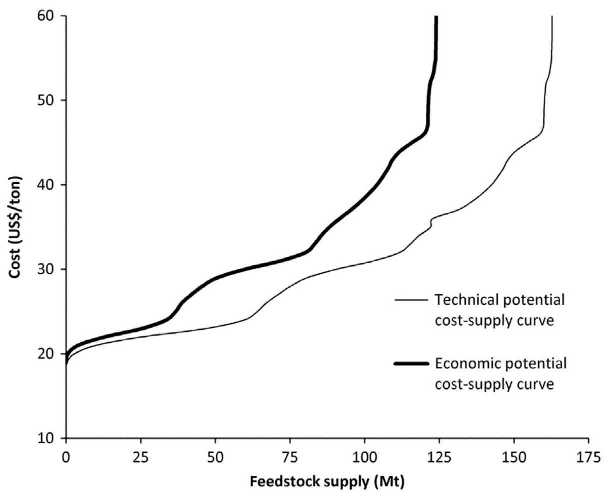

Fig. 15. Cost–supply curve of the technical and economic potential of switchgrass cultivation given the land availability in 2030 in the PS scenario.

Since this modelling approach is based on the extrapolation of past short-term land use trends, the results of long-term scenarios should be interpreted with caution. High volatility in political and market conditions can be expected over the considered time period, especially in a country such as Argentina, where agriculture and livestock production are highly regulated and policy frameworks are rather unstable. Thus the results should not be taken as a prediction, but instead as a projection of possible future outcomes according to trends currently observed.

An attempt to refine the land-use classification was made, in order to provide a more detailed representation of agricultural production in Argentina. This approach allowed improving the characterisation of the land-use system, by explicitly incorporating different types of production systems and their spatial distribution within the model. However, a generalisation of several characteristics was necessary to maintain the model operational at the national level, while the profiles of the existing production systems show a large degree of regional variability in terms of productivity, labour structure, technology adoption and land ownership, sometimes even in small extent areas [42,60]. Therefore, it should be kept in mind that although the present study provides a reliable overview of the expected general developments at regional level, its findings should nevertheless be further researched at local scale in the most relevant areas, using more accurate and locally specific data.

A global land-use/cover map was used as the reference base map. However, this type of datasets is frequently fraught by inconsistencies such as ambiguous legends, relatively low accuracy and lack of interoperability [61]. Despite the effort to correct the original map (see Appendix A), misclassification issues were still found in some areas, particularly in the west and south-eastern area of Buenos Aires province, where crop and pasture systems

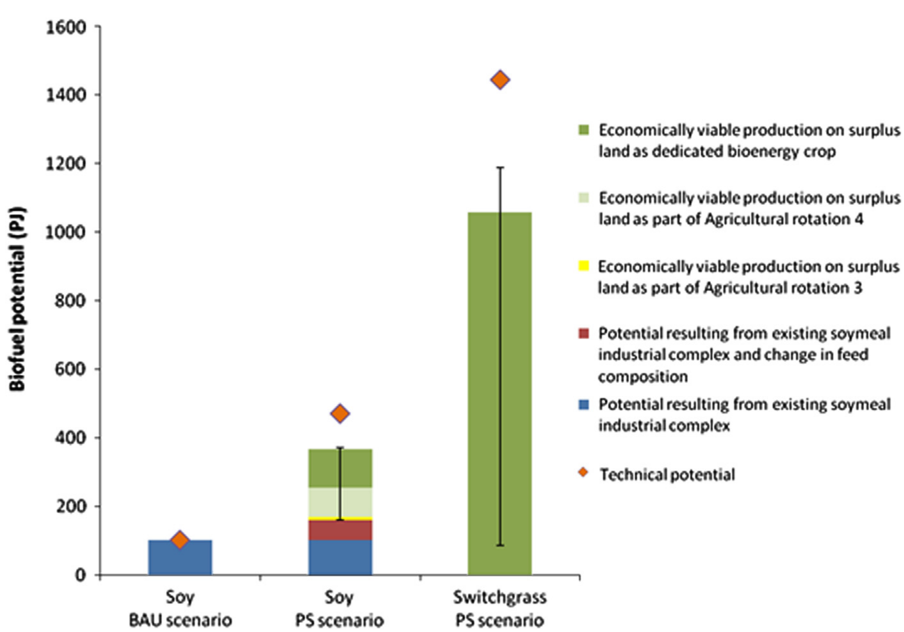

Fig. 16. Ranges of variation in biofuel production potential of soy biodiesel and switchgrass ethanol in 2030 for the BAU and the PS scenario given the optimistic- and pessimist- cases.

appeared to some extent to be interchanged [62] (further explanation is provided in Appendix F). This might have affected the results of both allocation of future agricultural production and availability of surplus land in this region.

It should be also noted that the present case study did not take into account the enforcement of the Forest Law (*Ley no. 26331/2007*), which defines the areas where agricultural expansion is allowed to take place and where it is restricted (see Appendix B.2). This presents an important limitation on studying the impact of agricultural expansion and livestock displacement on deforestation under current trends. However, the results can still be interpreted as an indication of possible future developments in case of law enforcement failure.

The use of yield reduction maps allowed to assess both the amount of land required to supply the expected demand for agricultural commodities and the economic performance of competing production systems. An underlying assumption of such an approach is that the maps are static and maximum local yields are always attained, which is to some extent an unrealistic premise, since short-term events such as ground frost, draught or excess of rainfall and long-term dynamic processes such as climate change and soil erosion may take place. Therefore, the model might be over-optimizing the capacity of the land-use system for delivering food production and as a result, land availability can be actually lower than what is being determined by the model. Nevertheless, the present study was able to provide an indication on what could be attained under optimal biophysical circumstances.

Furthermore, it should be noted that in the economic assessment, commodity market prices were assumed to remain unchanged for the considered timeframe, while in fact they can fluctuate strongly. Future studies on the economic potential should aim to explicitly incorporate price formation mechanisms in order to take into account possible feedback loops, e.g. by incorporating computable general equilibrium (CGE) models in the modelling framework. Such a multimodel approach has already proved to successfully simulate land-use patterns taking into account economic processes and driving forces operating at multiple scales. For example, Verburg et al. [25] have determined future aggregated demand for cropland and pastures in different world regions coupling together a global CGE model and an integrated global environment model, to then simulate agricultural land use with a high resolution at the regional level. Such a framework could be ultimately expanded further by explicitly considering crop prices and the cost of production factors determined through economic modelling as input to assess the relative economic performance of alternative crops and existing production systems. Nonetheless, this study was able to explore possible ranges of economic potential, through sensitivity analysis of biofuel crops' economic performance to market prices.

Although the impact of variations in a number of key factors was explored in the economic assessment, it would have been also interesting to assess the role of factors such as risk perception and cost reversibility in the economic viability of biofuel crops. For instance, farmers may prefer to continue cultivating crops that are less profitable but also less vulnerable to changes in climate features and/or market volatility than switching to and investing in a more profitable crop that is associated with higher risks. In this context, real option valuing might be an alternative method worth to explore in further assessments of biofuel potential of perennial crops [63].

4.2. Results

The present study showed that under the conditions of the BAU scenario, no land is expected to become available for dedicated biofuel production. However, Argentina holds currently a unique position in world's biofuel markets due to the existence of a technologically advanced agricultural sector and a well-established industrial complex for soybeans crushing. Therefore, soy biodiesel potential is likely to keep increasing steadily in forthcoming years, though production volumes will depend to a larger extent on the relation between the prices of soyoil and biodiesel (i.e. on the attractiveness of further converting soyoil to biodiesel) than on land availability (see [51] for a more detailed account on the drivers determining the rate of conversion of soyoil to biodiesel).

The PS scenario showed that only if major technological developments take place in the agricultural sector and particularly in the livestock production sector, land could become available in some regions. The area of east La Pampa and southwest Buenos Aires was identified as the region with the highest economic potential of biofuel production from switchgrass, due to land availability and good economic performance. These results are in line with historical trends of agricultural land abandonment in the less suitable areas of La Pampa province [64–66] and with the findings of Van Dam et al. [13], which also identified the province of La Pampa as a promising region in terms of land availability for the large-scale deployment of switchgrass. However, so far there is very limited experience in commercial exploitation of switchgrass in Argentina and therefore large uncertainties still exist regarding market prices and attainable yields, which were shown to have a great impact on the economic performance and resulting potential. It should also be noted that other options might be already available for biofuel feedstock, without depending on future developments on land availability. For instance, large volumes of crop residues and wastes are currently produced every year in Argentina, which in fact could become available for bioenergy production in the short term [67].

Distance to markets and ports was taken into account as an allocation driver without considering the capacity of ports and their share on the exportation of food commodities. For instance, the ports surrounding Rosario city have substantially larger capacity and trade volumes than the remaining ports. Therefore, it would be important to investigate to what extent the considered ports would actually have enough capacity to handle the determined biofuel potentials.

4.3. Sustainability of soybean production

Unlike other first generation conversion routes, soy biodiesel production offers the possibility of being coupled with food production, thus potentially avoiding issues resulting from competition for land at a larger scale. However, other concerns on the sustainability of soy cultivation in Argentina have been raised as follows: homogenisation of the agricultural landscape [55] and soil degradation due to monoculture practices [68–70], degradation of water availability and quality [68,69,71,72], negative health impacts in rural communities, land tenure issues and loss of livelihoods of indigenous populations and small-scale farmers in regions where soy has been recently introduced [58,73]. Addressing these issues was, however, out of the scope of this assessment, since the underlying processes are to a great extent location-specific and therefore could not be fully captured in a study at regional level. An account on recent developments of sustainability certification of soy biodiesel in Argentina can be found elsewhere [49].

5. Conclusions

In this paper, a spatiotemporal land use modelling framework combining an empirical and a theory-based approach was presented

and demonstrated for a case study in Argentina in order to assess future developments in land availability and economic potential of biofuel production from soybeans and switchgrass up to 2030 without causing iLUC, while taking under land functions into account. The empirical approach explored the dynamic features of the land use system in providing the expected demand for food products and assessed the availability of surplus land. It was found that according to the BAU scenario no surplus land is expected to become available and therefore the technical potential for switchgrass ethanol production is nonexistent. Biodiesel production from soybeans is nevertheless expected from the existing soy complex for feed production and according to current trends a technical potential of 103 PJ could be expected in 2030. According to the PS scenario, in which large technological developments in the agricultural and particularly in the livestock sectors are assumed to occur, 32 Mha could become available for dedicated biofuel production, which would allow for a technical potential of 472 PJ soybean biodiesel and 1445 PJ switchgrass bioethanol. The theory-based approach aimed then to assess the economic viability of growing biofuel crops on the available surplus land in order to determine the economic potential. Taking into account the profitability of competing agricultural production systems, an economic potential of 368 PJ of soybean biodiesel and 1.1 EJ switchgrass ethanol could be attained by 2030 in PS scenario, at a feedstock production cost of 100–155 US$/ton and 20–45 US$/ton, respectively. Areas currently used as pastures in the region of southwest Buenos Aires and La Pampa provinces appeared to be particularly promising for switchgrass cultivation. These areas have low suitability for conventional crops, and therefore a high-yielding perennial crop such as switchgrass could become an attractive alternative for farmers in this region. This finding is line with previous research on biofuel potential in Argentina [13].

It was found that the potential for soybean biodiesel is likely to keep increasing in future decades due to the existence of a highly developed industrial complex and agricultural sector. Technological options such as agro-industrial systems combining feed, food and bioenergy production in closed systems could present opportunities to simultaneously increase the existing biofuel potential and avoid indirect land-use changes resulting from livestock displacement.

The determined potentials are considerably lower than those obtained in a previous study [13]. Not taking into account the whole country area and not including learning effects on biofuel production may partly explain the lower results. The incorporation of an economic component in the assessment also provides an explanation for the large differences. The advantage of including an economic assessment within the modelling framework is that it allowed to take into account not only land availability but also economic viability as a key factor for the determination of biofuel potential, being therefore more informative than previous assessments in regard to the contribution of sustainable biofuels to energy supply systems.

Large uncertainties still remain regarding the potential of switchgrass for biofuel production as follows: (1) there is little practice of commercial cultivation and a market is still inexistent; (2) the availability of land depends to a large extent on the developments in technology adoption, particularly in livestock production. Therefore, switchgrass ethanol should be essentially regarded as mid-term option, since the required conditions in terms of market creation and land availability may take time to develop. Nevertheless, the present study was able to inform and provide insights to policy makers on how to steer and promote the use of such a crop for biofuel deployment and achieve the identified potential.

In conclusion, the proposed framework proved to be able to reproduce current land use trends and determine future developments on technical and economic potential avoiding iLUC, while identifying the regions where these potentials are more likely to be achieved. The proposed framework provides a generic methodology that is suitable to be applied in other geographical regions, to better inform policy-makers and investors on the use and management of land resources and on the economic viability of large-scale bioenergy projects complying with sustainability criteria.

The combination of two different types of the modelling approach within a single framework is line with Verburg et al. [21], which advocates the use of different land use modelling approaches in order to study complementary aspects of land use systems and provide more direct linkages between processes and patterns. However, despite the incorporation of an economic component, economic processes such as price formation and trade in the global economy were not represented in the framework. A possible improvement in further research could entail coupling economic modelling in the land use modelling framework, e.g. through the use of computable general equilibrium models. In addition, valuation methods such as real option valuing can also provide an alternative approach to access the role of investment risk perception and cost reversibility in the economic attractiveness of newly introduced biofuel crops.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.02.040.

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